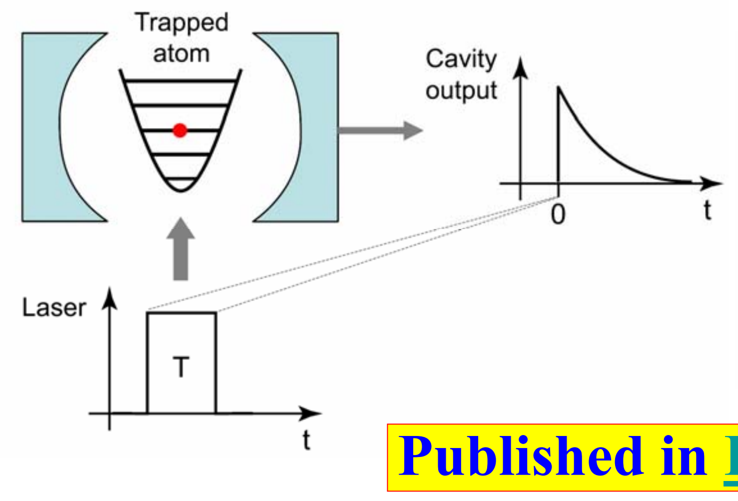
Entangled light pulses from a single cold trapped atom

Giovanna Morigi,[1] Jürgen Eschner,[2] Stefano Mancini,[3] and David Vitali[3]

[1]*Grup d'Optica, Departament de Fisica, Universitat Autonoma de Barcelona, 08193 Bellaterra, Spain*
[2]*ICFO—Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain*
[3]*Dipartimento di Fisica, Università di Camerino, 62032 Camerino, Italy*



The coherent interaction between a laser-driven single trapped atom and an optical high-finesse resonator allows to produce entangled multi-photon light pulses on demand. The mechanism is based on the mechanical effect of light. The degree of entanglement can be controlled through the parameters of the laser excitation. Experimental realization of the scheme is within reach of current technology. A variation of the technique allows for controlled generation of entangled subsequent pulses, with the atomic motion serving as intermediate memory of the quantum state.

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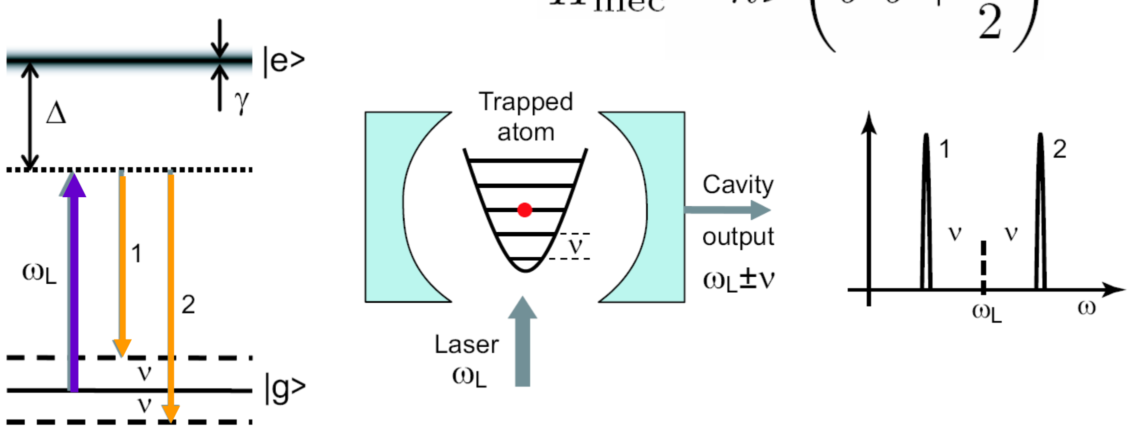
Bichromatic pulses

Bimodal high-finesse cavity (laser ref. frame)

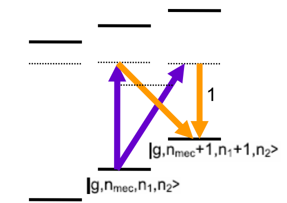
$$H_c' = \hbar\nu(a_1^\dagger a_1 - a_2^\dagger a_2)$$

Quantum center-of-mass motion (Lamb-Dicke regime)

$$H_{\rm mec} = \hbar\nu\left(b^\dagger b + \frac{1}{2}\right)$$

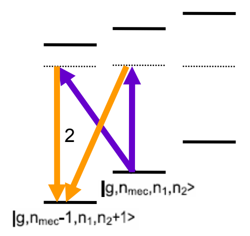


Effective coherent dynamics $H_{\rm eff} = H_c' + H_{\rm mec} + H_1 + H_2$



Two-mode squeezing interaction

$$H_1 = i\hbar\chi_1 a_1^\dagger b^\dagger + {\rm H.c}$$



Beam-splitter interaction

$$H_2 = i\hbar\chi_2 a_2^\dagger b + {\rm H.c}$$

Periodic dynamics for $|\chi_2| > |\chi_1|$, frequency $\Theta = \sqrt{|\chi_2|^2 - |\chi_1|^2}$

for $T_\pi = \pi/\Theta$ -laser pulse duration- with $\kappa \ll \frac{1}{T} \ll \nu$

State of cavity modes: $|\psi\rangle = \left(\frac{1-r^2}{1+r^2}\right)\sum_{n=0}^{\infty}\left[-\frac{2r}{1+r^2}e^{i\phi}\right]^n |n,n\rangle$

Squeezing parameter: $r = \left|\frac{\chi_2}{\chi_1}\right| \approx 1 + 2\frac{\nu}{\Delta}$

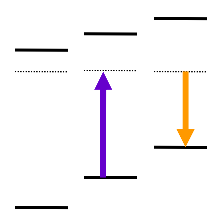
The cavity modes are EPR entangled, the motion is decorrelated!

Temporally separated pulses

Single-mode high-finesse cavity (laser ref. frame), $\hbar\omega_c a^\dagger a$
Quantum center-of-mass motion (Lamb-Dicke regime)

Procedure:

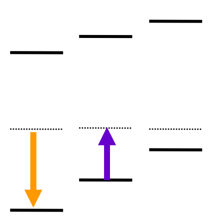
1) Two-mode squeezed state of motion and cavity mode
Laser pulse at $\omega_L = \omega_c + \nu$, duration T_1



$$H_{\rm eff}^{(1)} = \hbar\omega_c a^\dagger a + H_{\rm mec} + H^{(1)}$$
$$H^{(1)} = i\hbar\chi a^\dagger b^\dagger + {\rm H.c}$$

2) Cavity decay: Two-mode squeezed state of motion and propagating pulse

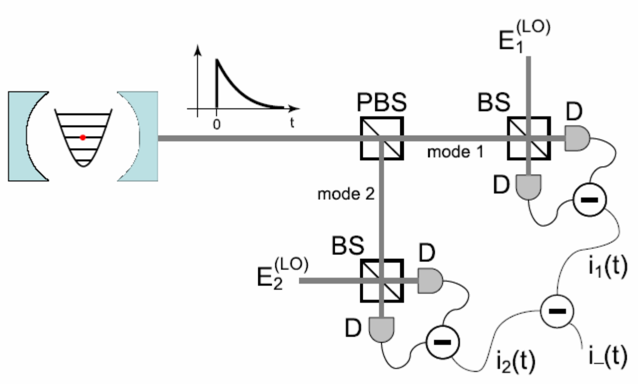
3) Quantum state transfer between motion and cavity mode
Laser pulse after $\tau \gg 1/\kappa$ at $\omega_L = \omega_c - \nu$



$$H_{\rm eff}^{(2)} = \hbar\omega_c a^\dagger a + H_{\rm mec} + H^{(2)}$$
$$H^{(2)} = i\hbar\chi a^\dagger b + {\rm H.c}$$

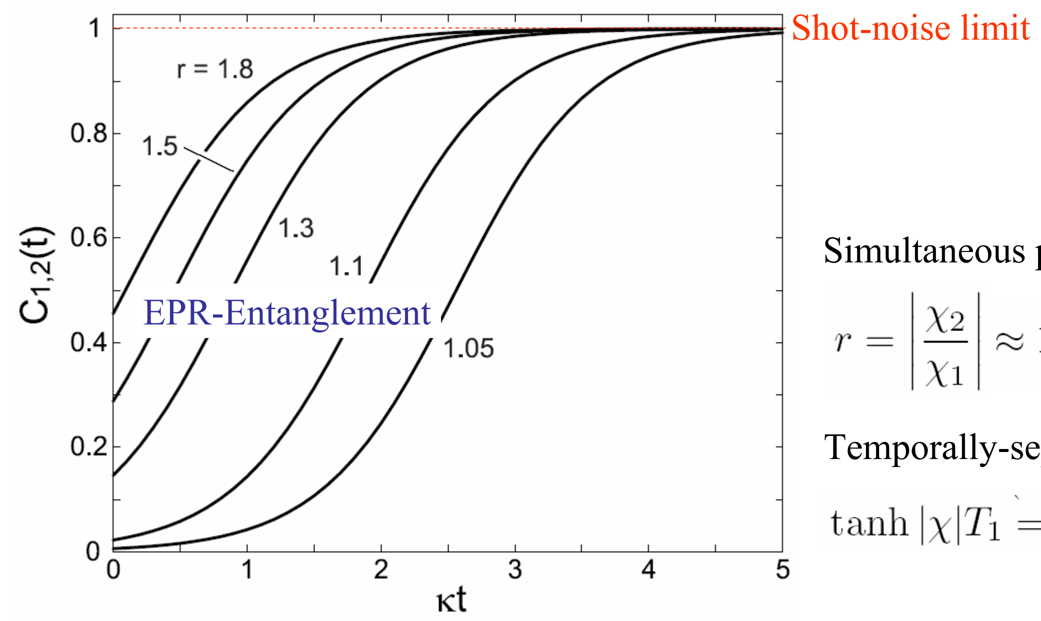
4) Cavity decay: **Two-mode squeezed state of temporally-separated propagating pulses. The motion is decorrelated!**

Field at the output: Correlations



Fluctuations of the difference current

$$\langle i_-(t)^2\rangle = i_-^{(0)} C_{1,2}(t)$$



Simultaneous pulses

$$r = \left|\frac{\chi_2}{\chi_1}\right| \approx 1 + 2\frac{\nu}{\Delta}$$

Temporally-separated pulses

$$\tanh|\chi|T_1 = 2r/(1+r^2)$$

Outlook.

Implementations in the microwave regime

Entanglement mediated by the collective excitations of ultracold gases, solid-state devices?

Study of correlations at the cavity output by laser continuous wave excitation.

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